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Focusing Hard X-rays at Current and Future Light Sources for Microscopy and High-Power Applications

R. M. Bionta, Lawrence Livermore National Laboratory.

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Introduction and Background

The field of x-ray optics struggles to develop optical systems with the versatility and sophistication of their visible light counterparts. The advent of fourth-generation light sources will make the struggle even more difficult.
Fourth-generation light sources include laser/plasma sources, x-ray Free Electron Lasers (FEL), inverse Compton scattering sources, and the National Ignition Facility. LCLS, (Linac Coherent Light Source), and its European cousin, will be the first of the x-ray FELs.

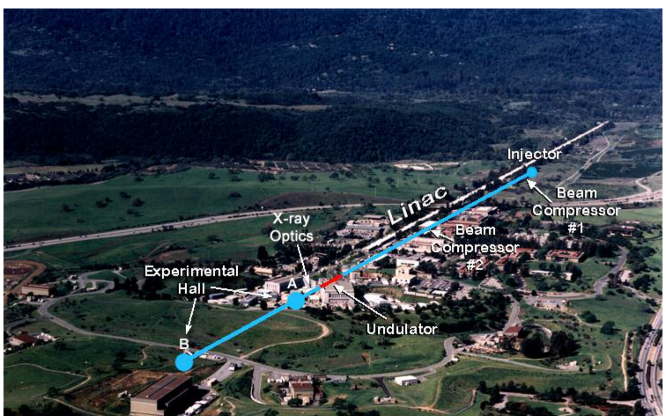


Figure 1: LCLS, a fourth-generation light source of unprecedented brilliance.

The LCLS, to be built at the Stanford Linear Accelerator Center (SLAC), takes advantage of the existing SLAC linear accelerator to send intense, low emittance electron bunches through a 100 m long undulator structure. Through a process called SASE (Self Amplification of Spontaneous Emission) the electrons interact with the radiation fields they produce while in the undulator causing them to collect into micro bunches that emit coherent light. In the case of the LCLS the coherent radiation will have a wavelength in the x-ray regime, and will be tunable from 1.5 to 15 Å. The LCLS will deliver x-rays in individual coherent packages lasting < 300 fs, making the LCLS a very important source for studying short time phenomenon and for performing high-resolution x-ray structural analysis of molecular sized systems. Moreover, each coherent packet packs 10^{12} photons in a very small volume of space time; the interaction of this packet with matter, and the subsequent aftermath offer new opportunities in physics.

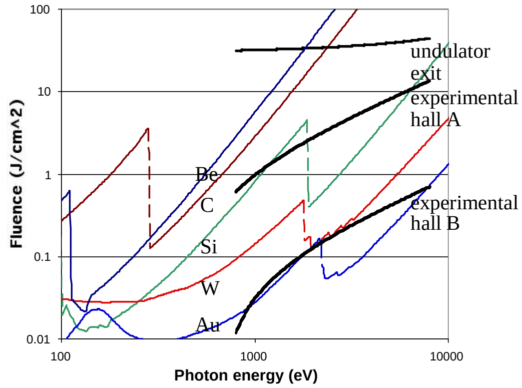


Figure 2: X-Ray Fluence needed to melt selected materials as a function of photon energy along with the expected fluences at the LCLS undulator exit and experimental halls.

To make full use of the LCLS, experimenters must be able to manipulate and focus the LCLS beam, and therefore must contend with the fact that the unprecedented energy density per unit area in the FEL beam is enough to melt most materials in a single pulse, (see figure 2).

Take the example of the Warm Dense Matter experiment, in which LLNL researchers hope to use a focused LCLS beam to instantly (that is fast enough that the density doesn't change) bring solid pieces of matter to a plasma state. The experiment operates with an 8 keV photon beam, and although the focusing requirements are modest, present-day x-ray optics that can meet these requirements will melt when exposed to the beam from the LCLS according to figure 2.

Figure 2 suggests that lower Z materials like beryllium, lithium, and carbon would fare better at the LCLS and that optics fabricated from low Z materials might offer a solution to the problem of survivable optics for the Warm Dense Matter experiment. Now both reflective and refractive x-ray optics are in use at these wavelengths, with reflective optics dominating because standard techniques have been developed for their manufacture. Common reflective optics make use of high Z materials which give higher performance. The less common refractive optics are also made of high Z materials but would work better if fabricated from low Z materials, which have less absorption. Based on these arguments it seems that low Z refractive optics would be the optics of choice for the Warm Dense Matter experiment.

The main objective of this project was to demonstrate that refractive optics for the Warm Dense Matter experiment could be fabricated from low Z materials, which would survive in the LCLS beam. We also wanted to gain familiarity with the LCLS so that LLNL experimenters would be better prepared to take advantage is of its capabilities. And finally, we wanted to understand how these technologies could be applied to programs within LLNL

Diamond turned blazed phase plate design, fabrication, and test.

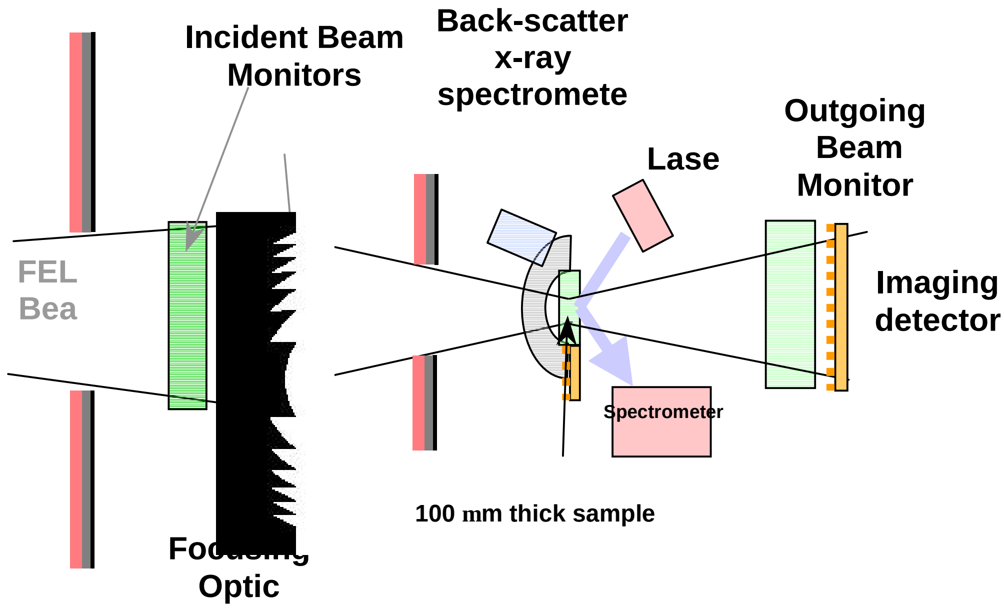


Figure 3: Layout of the Warm Dense Matter Experiment

A rough layout of the Warm Dense Matter experiment is shown figure 3. The 130 mm FWHM FEL beam enters from the left, passes through the beam monitor, and through the focusing optics. The converging beam from the optic strikes the sample 5.09 meters away. Focal spots at the sample of <10 microns FWHM are of most interest. With the lens situated 93.21 m from the source, the diffraction-limited spot on the sample is 5.68 mm. The lens would be 200 mm in diameter and have a focal length of 2.74 m.
The basic function of the lens is to change the phase profile of the diverging light from the source to the phase profile of a wave converging at the focus. In a refractive lens the phase change profile is obtained through a thickness profiles across the lens. The scale factor relating thickness to phase change depends on the x-ray optical constants of the lens material. Resetting the thickness every 2π phase changes results in a sawtooth radial profile called a blazed phase plate.

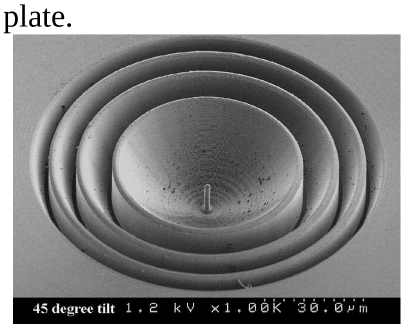


Figure 4: Blazed Phase Plate manufactured for the Warm Dense Matter Experiment

Although carbon is the best choice for the Warm Dense Matter experiment, we choose to fabricate our first lens of aluminum, which has the same optical constant at 8 keV as carbon, but was far easier to machine on the timescales available to this project. We manufactured the first lens of this type during FY 2001, shown in Figure 4. It is 100 microns in diameter. Each groove is 18.7 microns deep, which is the thickness in Al where 8 KeV x rays acquire an extra 2 π radians of phase shift with respect to x rays traveling the same distance in vacuum. The grooves were carved via single point diamond turning using a custom diamond point specially manufactured to have a 17 degree tip angle. The small pillar in the center is difficult to remove but has negligible effect on the performance of the lens. The carved disk was subsequently flipped over and thinned down from the backside to a final thickness of 79 microns.

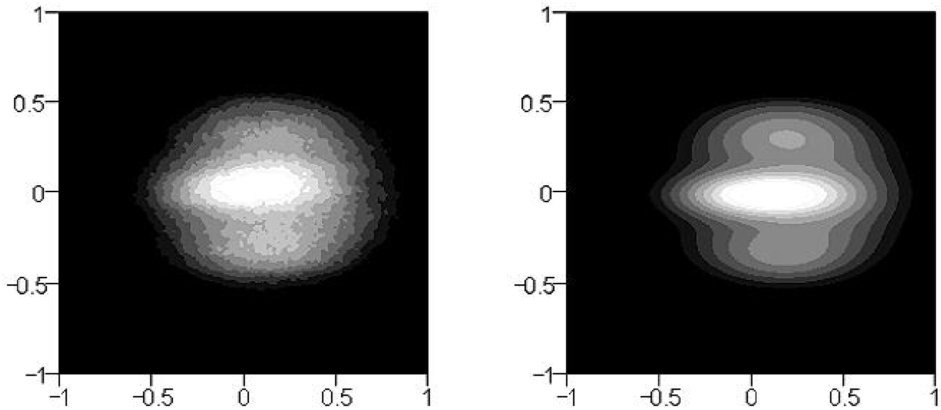


Figure 5: Measured (left) and simulated (right) images from the Warm Dense Matter lens.

This lens was tested at SSRL (Stanford Synchrotron Radiation Laboratory) by placing it 16.8 m from a bending magnet light source, and recording the image 1.7 m downstream of the lens. The image was recorded one pixel at a time by scanning a 10 micron pinhole across the image plane and recording the number of photons passing through the pinhole with a selection diode. The resulting image is shown figure 5a alongside a simulated image in figure 5b. The large illuminated circle in both images is the light passing through the 250 micron hole in the lens mount. The elliptical bright spot in the center is the x-ray image of the electron beam passing through the bending magnet. The similarity of the observed and predicted images is evident. Careful analysis of the amount of x-ray photons collected under the elliptical peaks show that the lens is actually collecting 57% of the light collected in the simulations.

X-ray Imaging Camera

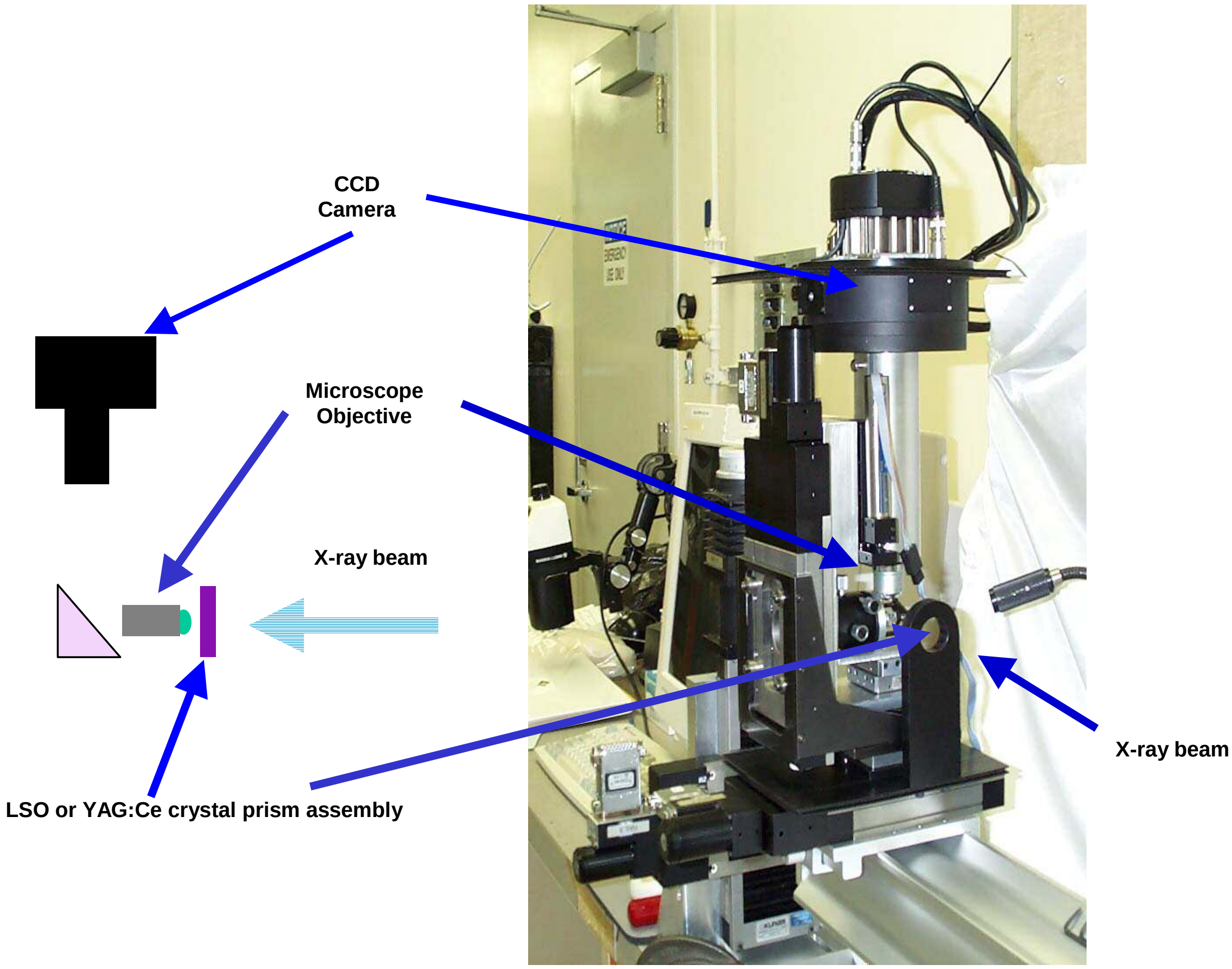


Figure 6: X-Ray Imaging Camera.

The scanning pinhole technique allowed us to test our first lens, but was painfully slow. Each image required almost an hour of beam time to record, precluding systematic studies of lens performance vs. tilt for example. To solve these problems, we developed the scintillator/CCD microscope-imaging detector shown figure 6. The detector utilizes a 25 to 100 micron thick scintillating crystal composed of LSO or YAG to convert x-ray photons into visible light. The visible light is captured by a high performance microscope objective and reflected into a 1K x 1K thermal electrically cooled CCD camera. The assembly includes precision motion stages to adjust the horizontal and vertical position of the camera, the distance from the objective to the crystal, as well as the tip and tilt angles of the crystal plane with respect to the object plane of the microscope objective.

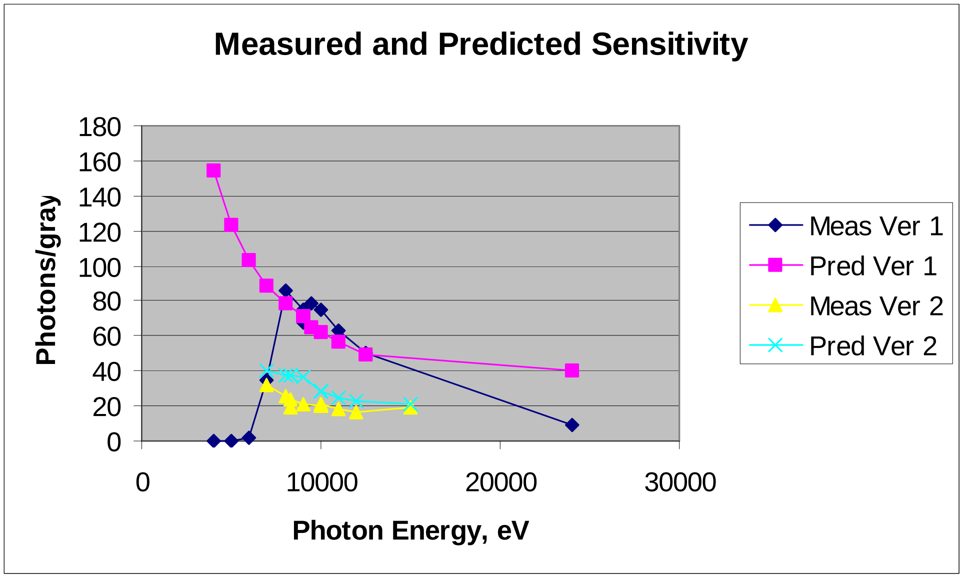


Figure 7: Measured and predicted sensitivity of two versions of the camera.

The performance of the camera was measured during the second run at SSRL. The camera sensitivity was measured by comparing the sum of the digital gray level response to the number of photons registered in an ion chamber as a function of beam intensity. These measurements were compared with numerical simulations of the photon transport in the scintillator and microscope objective and found to be in fair agreement for range of photon energies from 4 keV to 25 keV, see figure 7.

The camera resolution was also determined in these runs by measuring the line spread function from images of slits. The thin scintillator, the microscope objective numerical aperture, and the CCD pixel size were chosen to give a resolution of one pixel, corresponding to 4.8 microns in the object plane. Figure 8, which is a partial image of a beryllium disk, shows that one pixel resolution was achieved.

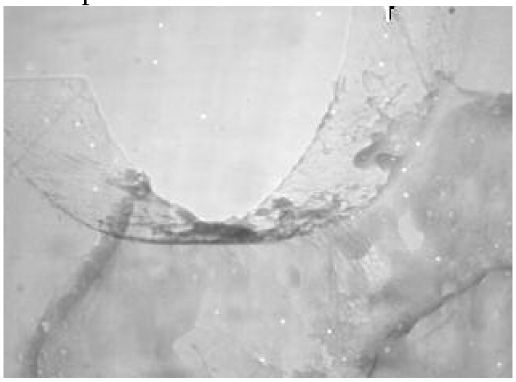
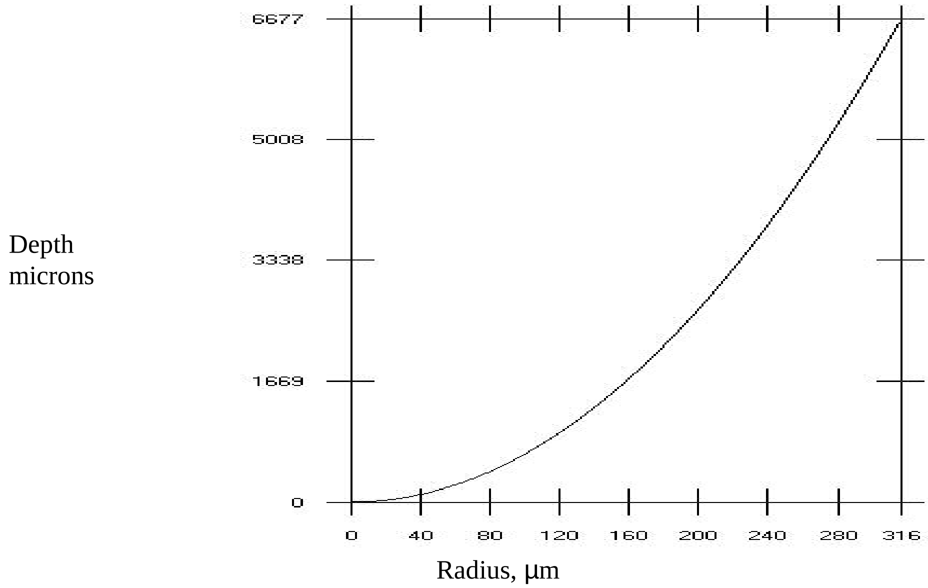


Figure 8: Partial image of a Be disk.

Fabrication and Testing of Beryllium Refractive Lenses

Figure 9: Profile of a large aperture Be lens.



In the final year of the project, as an alternative to the carbon blazed phase plate structure described above, we fabricated and tested an x-ray analogue of a simple refractive lens using the most stable transparent material we could find-Beryllium. Because of the very small optical power of Beryllium at 8 keV, a lens with a focal length of 1.5 m, that has a diameter of 670 microns, must be 6.6 mm long, figure 9. This was accomplished by sectioning a 6.6 mm thick block of Beryllium into four quadrants, and carving the lens profile into the inner corner of each quadrant.

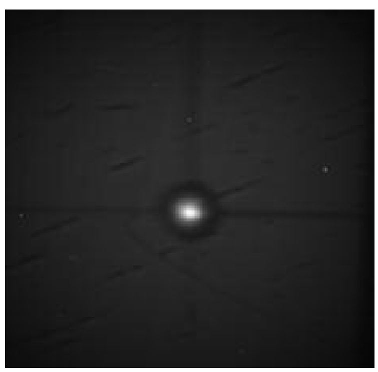


Figure 10: Image of the SSRL source produced by the Be lens.

The lens was tested at SSRL in the same setup used to test the Al lens. Figure 10 shows the image obtained in the image plane of the lens. The dark circular area in the center is the shadow of the lens, and the boundary of the 4 quadrants is evident as the dark cross through the center. The image of the source is the bright elliptical area in the center. This image is very different than what wasexpected of this lens. The amount of light in the central peak is < 5% of what was expected. In addition the observed width of the spot in the vertical direction is much broader than expected. These two observations imply that the lens performance is poor.

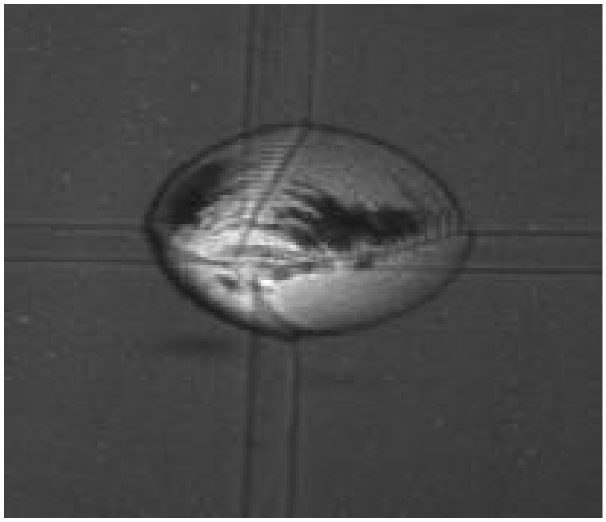


Figure 11: Radiograph of the Be lens.

Clues to the poor performance can be found from radiographs of the lens taken at SSRL as shown in figure 11. This radiograph was obtained by placing the camera very close to the lens. The radiographs reveal dark marks suggestive of surface problems associated with the tool, which may be the cause of the poor performance.

Summary

We have attempted to design, fabricate, and test refractive lenses designed for 4^{th} generation light sources like the LCLS using to different methods. We had to develop an x-ray imaging system to test the lenses, achieving 4 micron resolution over a 5 mm area,. The sensitivity of the camera was as expected. Of the two methods for producing transmissive lenses, those produces by direct diamond turning of a blazed phase profile had the best profile. The higher performance Be design performed poorly and evidence indicates that the surface quality is the problem.

Auspices Statement

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